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The European Office of Aerospace Research and Development's Small Satellite Propulsion System Research Program

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Abstract

A spacecraft needs propulsion for attitude control, stationkeeping, and orbit maneuvering. Traditionally, these needs have been satisfied by the following system options:

- Cold-gas propulsion – mainly using nitrogen for attitude control
- Hydrazine-based systems – for attitude control, station-keeping and orbit maneuvering
- Solid rockets – for orbit maneuvering

However, the space industry trend to build smaller and cheaper spacecraft (10 – 300 kg) have created propulsion system integration requirements and constraints unique to these niche applications. The European Office of Aerospace Research and Development (EOARD) has started a program with 3 European institutes to investigate these niche systems for future Air Force small satellite propulsion missions:

- **Nitrous oxide monopropellant, University of Surrey, UK**: a self-pressurizing, nitrous oxide catalytic decomposition technique is suggested for re-startable spacecraft propulsion. More than 50 different catalysts have been tested. Catalyst activation temperature of 250°C has been achieved with mass flow rates above 1.1gm/s. Decomposition temperatures in excess of 1500°C have been attained. Electrical power input (for heating the catalyst up to its activation temperature) as low as 24W has been applied. The time required to heat the catalyst from ambient to activation temperature was as short as 3min. A catalyst lifetime in excess of 76min. has been demonstrated. Work will continue to find the optimum catalyst to meat spacecraft lifetime requirements.
- **100 W Stationary Plasma Thruster (SPT), Fakel Design Bureau, Russia:** An SPT works by developing an axial electric field between discharge electrodes. Due to the lower power, Fakel decreased the thruster size to 50-mm diameter x 40 mm in length (size of a 35-mm roll of film). They also varied the xenon flow density and magnetic field intensity to try to increase the performance. Fakel also developed a cathode (no heat required compared to other cathode designs) that is roughly the size of a standard ink pen. The thruster total mass is 350 g. Thruster tests covering a total of 9.5 hours at various settings were observed, including the following significant results (all stated efficiencies include the cathode): Input power: 94.5 W Thrust: 4.7 mN Specific Impulse: 1000 sec Efficiency: 24 %

Paper presented at the RTO SET Symposium on "Space-Based Observation Technology", held on the Island of Samos, Greece, 16-18 October 2000, and published in RTO MP-61.

- **Modification of the T-27 Thruster for 100 W Use, Tsniimash, Russia:** Tsniimash varied the flow and power conditions of their existing 200 W SPT T-27 thruster and operated it at 100 W. Although the efficiency decreased from 35 % to 23 % for the lower power operation, the thrust and Isp were good for small satellite application at 5 mN and 981 sec respectively.

The paper will go into greater description of these programs and will conclude with future work planned.

Introduction

The success of small satellite missions depends on low-cost launch opportunities. So far, the majority of small satellite missions have been as secondary payloads deployed into LEO (low Earth orbit). Unfortunately, until now these spacecraft lacked one critical system that would allow them to exploit fully emerging opportunities in LEO and beyond— a propulsion system. Propulsion systems are a common feature on virtually all-larger satellites. However, until now there has been no need for very small, low-cost satellites to have these potentially costly systems. As secondary payloads, they were deployed into stable, useful orbits and natural orbit perturbations (drag, J2, etc.) were acceptable within the context of the relatively modest mission objectives.

Over the years, these pioneering small satellite missions have proven that effective communication, remote sensing and space science can be done from a cost-effective platform. As these missions have evolved, various technical challenges in on-board data handling, low-power communication, autonomous operations and low-cost engineering have been met and solved. Now, as mission planner's look beyond passive missions in LEO to bold, new missions which require active orbit and attitude control, a new challenge is faced—cost-effective propulsion.

In order to compete in the commercial market, small satellites have other unique constraints compared to larger spacecraft:
1. Cost < £4 million
2. Mass - < 500 kg
3. Volume - < 600 mm outer diameter x 800 mm length
4. Power - < 150 W on orbit average in LEO
5. Integration - safety, logistics of propellant transfer to launch site and handling of non-toxic propellants
6. Thrust - attitude control thrust < 1 N vs. high drag orbit thrust > 1 mN

Table 1 shows a comparison of various propulsion systems for a 100 kg spacecraft requiring a ΔV of 200 m/s. This mission velocity could move a 100 kg spacecraft from an circular orbit of 200 km to 600 km altitude or provide initial separation and phasing, 3 years stationkeeping, and deorbiting for each spacecraft in a 4 – 6 sunsynchronous constellation.

System	N_2 Cold Gas	N_2O Liquid gas	100 W Nitrous Oxide Resistojet	Nitrous Oxide Monoprop.	Hydrazine Monoprop.	100 W Stationary Plasma Thruster (Hall Effect)
Propellant Mass (kg)	26.9	29.6	14.5	11.3	8.9	2.0
Propellant Volume (l)	330.4	38.1	18.7	14.5	8.0 + press.	3.4
Time (hours)	23.5	23.5	23.5	23.5	23.5	747.4

Table 1: Comparison of Various Propulsion Systems for a 100 kg satellite, $\Delta V = 200$ m/ s

Table 1 presents interesting results. Current off-the-shelf cold gas systems would offer little/no volume for the payload. The nitrous oxide monopropellant system gives similar

performance to hydrazine (48 bar vapor pressure requires no pressurent), but is non-toxic which makes it much better to handle logistically. The Stationary Plasma Thruster (SPT) offers very good performance, but will require more time to get the satellite on station. All of the other systems are scalable to different thrust levels with little impact on performance (except for the resistojet, which will require more power to maintain performance at a higher thrust). I assumed 100 mN since that would allow integration into a 100 kg spacecraft with little impact on the attitude control system (disturbance torques can be controlled by wheels and magnetorquers).

Figure 1 shows a comparison of the various systems as a function of density specific impulse and amount of power needed from the satellite to produce thrust. Density specific impulse is defined as the specific impulse of the propellant (mass performance) multiplied by its average specific gravity in its storage state. The ideal system for a small satellite would produce a high density specific impulse and require no power, which would be in the upper left hand corner of the figure. The goal of the EOARD propulsion program is to investigate such a system, but also keep the cost below current off the shelf hydrazine systems.

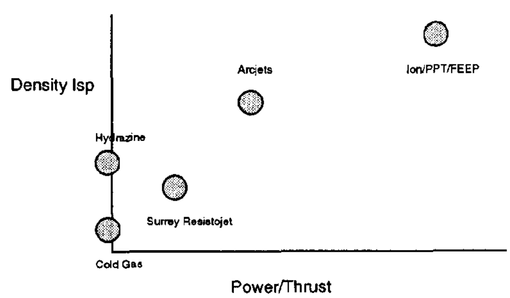

Figure 1: Power/Thrust ratio versus Density Specific Impulse

Nitrous Oxide Monopropellant

The University of Surrey, Guildford, UK started an investigation into low cost propulsion systems for their microsatellites (50 – 100 kg) in 1995. After analyzing the various options, they discovered that water and nitrous oxide resistojets looked attractive for its future missions. In 3 years of development time, they produced the Mark IV thruster. This thruster was flown on the UoSAT-12 (University of Surrey 300 kg satellite) and flight qualified for the USAF MightySATII.1 program – work sponsored by AFRL/PRRS and EOARD. Figure 2 shows the two thrusters. Figure 3 shows a sectioned view of the thruster. It can be seen that the thruster is itself very simple in construction, which leads directly to the low unit cost feature, which was very much the design aim from the beginning. The key science problems solved was in the choice of bed material for heat transfer and material compatibility, high heat transfer to the working fluid at low power, and optimum nozzle size due to friction losses.

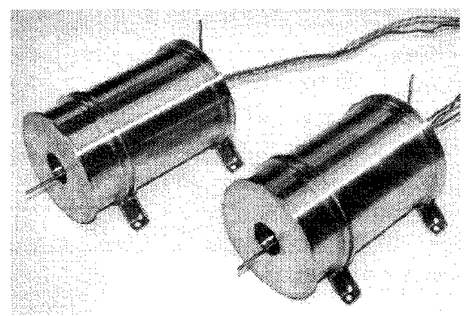

Figure 2: Mark IV standard thrusters

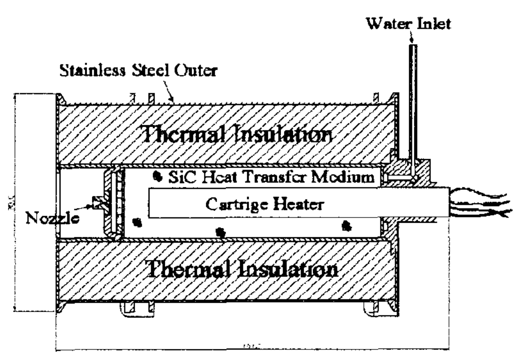

Figure 3: Section view of resistojet

To date two applications have been found for the Mark IV resistojet. The USAF intended to fly

one version on their MightySat II.1 program. The system was designed to operate with water as propellant. For various reasons this system was deselected as a baseline and the spacecraft will fly no propulsion system.

The other application was Surrey's own R&D spacecraft UoSAT-12. This system already had a cold gas nitrogen propulsion system as its baseline. However there was sufficient mass budget available to add an experimental nitrous oxide resistojet system at a late stage of the build program.

Table 2 below details both flight systems: -

Life duration testing using deionized water. From 13th to 30th June 2000 at SSC under ambient conditions. A total lifetime of 423 hours demonstrated with throughput of 29 kg of water. Post testing performance checks did not show any anomalies. The thrust results are shown in Figure 4.

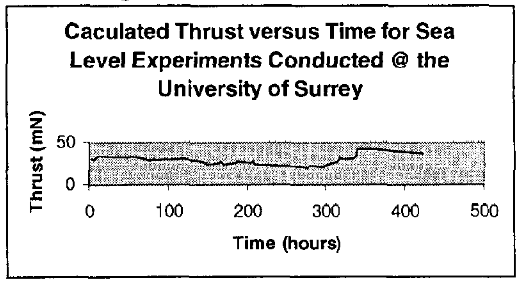

Figure 4. Endurance Test of Mark IV thruster

Item	UoSAT-12 Specifications	MightySat II.1 Specifications
Working fluid	Nitrous Oxide	Water
Chamber pressure	10 bar (~48 bar storage)	5 bar (10 bar inlet)
Mass flow	0.0001 kg/s	0.000066 kg/s
Power	91 W @ 28 V	100 W
Resistojet mass	1.2 kg	1.2 kg
Expulsion system mass	10.75 kg	6 kg
Propellant mass	2.3 kg	1.1 kg
Isp at steady state	127 sec	152 sec
Thrust	125 mN	75 mN
ΔV	~ 9 m/s	16 m/s
Nozzle	0.4 mm throat spark eroded	0.3 mm
Assembly	Electron beam welded	Electron beam welded

Table 2: Mark-IV System Specifications for the UoSAT-12 and MightySATII.1 Missions

MightySat II.1

An Engineering Model (EM) thruster was supplied to the USAF, however a flight unit was not supplied as the program was put on hold. Upon restart an alternative system was selected since the program office decided that MightySATII.1 no longer required a propulsion system. The EM was returned to SSC to allow a life demonstration program to be performed. Vibration testing of the unpowered EM took place on 31st May 200. Sine testing was up to 100 Hz and 15 g, and random vibration at 0.3 g2/hz (19.5 overall grams).

UoSAT-12

UoSAT-12 is a 300 kg experimental minisatellite. It was launched on a Dnepr launch vehicle from Baikonour, Khazakstan in April 1999. A Nitrous Oxide supply system with a Mark IV resistojet was fitted to the spacecraft.

The schematic of the propulsion system is shown below in figure 5. 2.3 kg of Nitrous Oxide was stored in three propellant tanks.

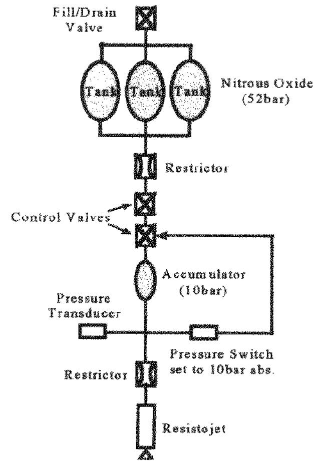

Figure 5: Nitrous Oxide feed system

Nitrous oxide is perfectly suited to this type of system as it is stored as a liquid, under its own vapor pressure of approx. 48 bar at room temperature; hence no pressurization system is required. Tank pressure is regulated to 10 bar using a pressure switch to control a solenoid valve giving a "bang- bang" regulator.

Since the system is designed for 100 W, one hour of continuous power is feasible during specific solar cycles of the orbit.

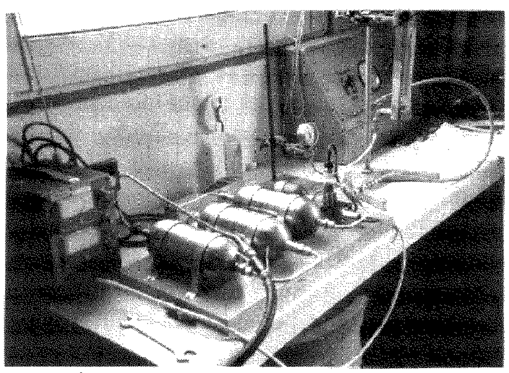

Figure 6: Polyflex Expulsion System

Figure 6 shows the expulsion system fabricated by Polyflex Aerospace Ltd, Cheltenham, UK. The system was shown to be able to support the 7 hour life time at the desired flow rate. Qualification tests were conducted in September 1998 with integration beginning in October of 1998 and were finished in December 1998.

The first on–orbit flight test was conducted on 26th July 1999. The thruster was fired for 15 seconds and produced an Isp of 93 sec, thrust of 95 mN, at a power of 91 W. Unfortunately the thrust vector was not aligned perfectly with the spacecraft C of G (off-set measured to be approximately 2.6 cm). The ADCS subsystem was not set-up for a torque to be generated by this firing and the result was to destabilize the attitude estimator filter, causing the AOCS not to remain nadir pointing. Spacecraft control was quickly regained, however no further firings were undertaken at that time. Investigation showed that the pressure reading saturated at 13 bar (maximum limit) compared to 10 bar which the pressure switch should have controlled to. It was concluded that the commercial grade pressure switch had failed and that the pressure control valve was permanently open. Since there is a viscojet in the system, this restricted the flow somewhat, but recent analysis shows the mass flow has increased from 0.1 to 0.13 g/s.

This phenomenon was confirmed by a longer firing on 11th April 2000. The performance results of this firing are shown in Figure 7. Subsequent to this it was decided to reprogram the control system, such that the pressure control solenoid valve was opened in a predetermined sequence. The valve sequence was programmed to be 100 milli seconds open and 10 seconds closed. On 16th June 2000 this sequence was run with the resistojet switched off (as no power was available). The pressure peaked out at over 10 bar with a saw tooth form giving 1 bar peak to peak. It was decided to reduce the ON time to 50 m sec to obtain a nominal thruster inlet pressure of 5 bar hence reduce the thrust to a level which would give a disturbance torque low enough for the AOCS to still be able to retain control of the spacecraft due to the CG offset. Further hot fire tests are planned for September 2000 when the spacecraft has available power.

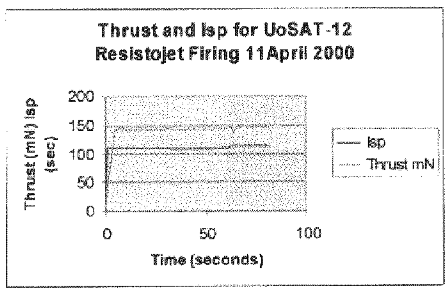

Figure 7: Thrust and Isp for 11 April UoSAt-12 Nitrous Oxide Resistojet Firing

One of the intriguing results that emerged from the Surrey resistojet research program was the exothermic decomposition of nitrous oxide. This was first observed in a resistojet test at Edwards AFB in January 1998. The thruster, similar design to the Mark-IV design described above, was initially heated to 600 C using the power system, and then the electric power was shut off and the system produced a steady state Isp of 148 seconds for 18 hours. The mechanism of this exothermic decomposition was thermal. It was noted that if catalytic decomposition could occur, the subsequent activation energy could be lowered and the reaction started at a lower temperature. This would be very attractive to small satellites since less power would have to be consumed. EOARD started a research program with the University of Surrey to investigate various catalysis in October 1999.

This thruster concept is based upon the catalytic decomposition of nitrous oxide and requires input energy at start-up, but then produces a self-sustaining reaction that runs as a function of the catalyst lifetime. Theoretical performance of the reaction is 206 sec. The University of Surrey has produced a ~ 1 N, 175 sec experimental apparatus that has been tested for 76 minutes continuously using a rhodium based catalyst. A picture of the apparatus is shown in Figure 8. The electrical power input was 24 W for 3 minutes, and then the reaction ran itself for the remaining 73 minutes.

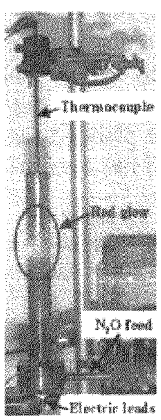

Figure 8: Nitrous Oxide Experimental Apparatus

Besides this accomplishment, the program has also achieved:

- Proof of concept was demonstrated
- Repeatable, self-sustaining, decomposition of nitrous oxide has been achieved using different catalysts
- Hot restarts at zero power input have been repeatedly shown in operation
- More than 50 different catalysts have been tested
- A catalyst activation temperature as low as 200 C has been recorded
- Nitrous oxide mass flow rates above 1.1 g/s have been supported
- Decomposition temperatures in excess of 1500 C have been demonstrated
- Electrical power input as low as 15 W has been used

The University plans on building a prototype thruster for vacuum testing in autumn 00. EOARD will investigate future collaboration in this program. EOARD also plans on co-sponsoring the upcoming ESA Green Propellants Conference in June 2001 at ESTEC.

Stationary Plasma Thrusters

As discussed previously, Stationary Plasma Thrusters (SPT) are attractive for small satellites, as long as their input power is not too demanding for the entire system (ppu, cathode, thruster magnetic field, valve) i.e. < 150 W. The problem is as the SPT's are scaled down from their traditional power of 1 kW, the losses dominate. The efficiencies of the kW thrusters are on the order of 50 – 60 % while the 100 – 150 W thrusters are 20 – 30 %. This loss in efficiency is attributed to a decrease in thruster size, which reduces the path for ionization and requires an increase in the flow density. The lower size also causes a higher magnetic field intensity and requires a different magnetic system.

However after discussions with Design Bureaus in Russia, efficiency is not as important a concern in small satellites. For low input power (~100W), it is more desirable to increase the thrust and lower the Isp and efficiency. These results were obtained in the research programs.

The first effort was with TSNIIMASH Export, Moscow, Russia and was a characterization of the performance of their existing T-27 thruster, operating at lower than design power conditions. They investigated the changes in performance due to variations in thruster power, mass flow rate, and magnetic field strength at powers ranging from 40 – 150 W. Their goal was to increase the ionization efficiency at a lower mass flow density and voltage. They deduced that the losses were too high even with these changes, and a new thruster had to be developed if a power < 100 W is needed. However the physics of small hall thruster operation were produced with an understanding of the important variables from this study. A picture of the T-27 is shown in Figure 9.

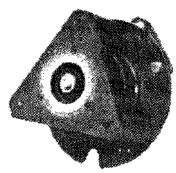

Figure 9: TSNIIMASH T-27 thruster

Fakel Design Bureau, Kaliningrad, Russia developed a new thruster to operate for the under 100 W power level. This thruster was a modification of the T-20 thruster that had been produced before, optimized for this power level and also required the development of a "heaterless" hallow cathode that could operate up to 1000 hours of operation. The thruster is shown in Figure 10 and produced the following results in 9 hours of tests at Kaliningrad:

Power: 94.5 W
Thrust: 4.7mN
Isp: 1000 sec
η = 24 % (includes cathode and other "system" power)

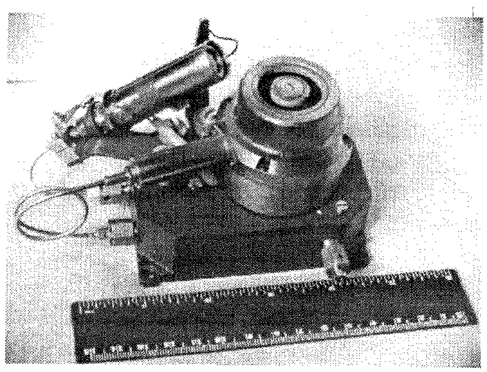

Figure 10: Fakel 100 W Thruster

This thruster has been delivered to Edwards AFB where it will undergo testing at the AFRL Electric Propulsion Laboratory to characterize its performance and estimate lifetime. Results of both of these programs will be published as EOARD reports through DTIC. Future work is also planned with Fakel in continuing the low power investigation.

EOARD is also working in SPT modeling research. Work has started with the University of Madrid to investigate 1 D modeling of the thruster plume. The University of ROMA is investigating the performance impacts of using superconductors on high power SPT's.

Future work is planned with Tsniimash to investigate the clustering of D-55 thrusters. Three thrusters will be fired continuously with different geometry locations and cathode placement. The plumes and power systems will be monitored to study the impact of "cross talk". The application of clustered thrusters and resultant modeling could enable future high powered SPT systems to be designed in modules.

Conclusion

This paper has shown some of the work sponsored by EOARD in small satellite propulsion. EOARD's mission is to directly support AFRL research goals by:

- Providing liaison with members of the European scientific community.
- Facilitating contact between AF scientists and their European counterparts.
- Contracting with European scientists to conduct research or support conferences and workshops

This basic research work will have an impact in helping to decide future propulsion systems for USAF, university, and commercial small satellite missions.

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